

Exotic Acceleration Processes and Fundamental Physics

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Gamma-ray bursts and ultra-high-energy cosmic rays provide an important testing ground for fundamental physics. A simple-minded analysis of some gamma-ray bursts would lead to a huge estimate of the overall energy emitted, and this represents a potential challenge for modelling the bursts. Some cosmic rays have been observed with extremely high energies, and it is not easy to envision mechanisms for the acceleration of particles to such high energies. Surprisingly some other aspects of the analysis of gamma-ray bursts and ultra-high-energy cosmic rays, even before reaching a full understanding of the mechanisms that generate them, can already be used to explore new ideas in fundamental physics, particularly for what concerns the structure of spacetime at short (Planckian) distance scales.

I. INTRODUCTION

Much of the work in astrophysics concerns the use of the presently-accepted laws of fundamental physics in the development of consistent descriptions of the observations. In some cases the key challenge comes from an energy-balance issue. For example, for some gamma-ray bursts the overall observed fluences can be as large as $10^{-4} \text{ ergs/cm}^2$, which would correspond to a luminosity of 10^{52} ergs/s and higher, if one can assume isotropy. It would be difficult to describe such levels of luminosity in terms of conventional physics. We now understand [1] that most gamma-ray bursts are narrowly beamed (not at all isotropic) and this lowers the luminosity estimate to a more mundane level; however, there is still no real consensus on the mechanism of emission of gamma-ray bursts.

Another energy-balance issue is encountered in the study of cosmic rays. In fact, recent data suggest [2] [3] that some cosmic rays have energies of 10^{20} eV and higher. And it has been argued [4] that at least some of these cosmic rays could originate from within our galaxy. But we are unable to find within our galaxy sources which are good candidates for accelerating particles to such high energies.

In the study of these issues some “exotic acceleration mechanisms” are being considered. Usually the relevant acceleration mechanisms are deemed “exotic” not because of some role for new laws of physics, but rather because of the role played by creative ways to rely on the presently-accepted laws of fundamental physics to devise mechanisms that could explain the energetics of the system of interest. Only in a few of the most speculative papers on these subjects it has been argued that new physics might be responsible for the emission mechanism.

While the possibility of new physics is at best a marginal hypothesis for the study of emission mechanisms, surprisingly these fascinating problems in astrophysics do provide, independently of the understanding of the emission mechanisms, some of the best arenas for testing ideas for new laws of fundamental physics, especially for what concerns the structure of spacetime at Planckian distance scales. We do not need to know exactly how gamma-ray bursts are emitted in order to observe that a gamma-ray burst is a very rich signal which propagates over very large distances. The analysis of gamma-ray bursts is therefore a wonderful opportunity for high-sensitivity studies of the laws of propagation of signals through space. Similarly we do not need to know exactly how a 10^{20} eV cosmic ray is produced in order to observe that the collisions between such a cosmic ray and the low-energy photons it encounters on the way to our Earth laboratories provide a rare opportunity to test the nature of boost transformations. In fact, the same collisions are studied in our particle-physics laboratories but only relatively close to the center-of-mass frame.

II. ON THE EMISSION OF GAMMA-RAY BURSTS

Even taking into account the fact that most gamma-ray bursts are narrowly beamed, in some cases the inferred luminosity is as high as 10^{51} ergs/s . This is still rather large but does not represent a record-setting energy release, since the total energy emitted is comparable to the one of supernovae [1].

The structure of a gamma-ray burst, viewed from a signal-analysis perspective, is extremely rich, and this of course represents a challenge for emission models. We need a model that would be able to reproduce faithfully all aspects of that rich structure. A popular idea is the one of the “fireball internal-external shocks model” [1], but it is perhaps too early to speak of a general consensus.

An example of the issues that are being discussed in the effort of establishing the emission mechanism is provided by the contribution by Kaneko *et al* [5], which stresses how important insight on the emission mechanism of gamma-ray bursts can be obtained by establishing the proper description of gamma-ray-burst spectra. On the basis of an interesting broadband spectral analysis of two spectrally-hard gamma-ray bursts Kaneko *et al* conclude that gamma-ray-burst spectra evolve on time scales that are much longer than the synchrotron cooling time. This may be consistent with some arguments discussed in the gamma-ray-burst literature (see, *e.g.*, Ref. [6]), but Kaneko *et al* argue that instead this should lead to the conclusion that the acceleration mechanism is more complicated than predicted by some popular gamma-ray-burst models.

III. GAMMA-RAY BURSTS AS A QUANTUM-SPACETIME LABORATORY

Gamma-ray bursts have recently attracted much interest (see, *e.g.*, the recent reviews [8] [9] [10] [11]) also from the research community exploring the hypothesis that spacetime might have to be “quantized”, *i.e.* that there might be a quantization of spacetime observables in a way somehow analogous to the quantizations of all other observables encountered in other aspects of fundamental physics.

Some scenarios for spacetime quantization involve a sort of granularity of spacetime, and as a result one may expect some departures from the smooth laws of Lorentz symmetry [15]. The mechanism would be analogous¹ to the one that applies to phonons: the law of propagation of phonons is formally relativistic at low energies, when the reticular structure of the underlying material can be ignored, but at high energies there are departures from the relativistic behaviour. If spacetime itself was granular then some analogous effect might be present. A sort of light-cone fuzziness is essentially inevitable in presence of spacetime granularity, and recently it was realized that some specific schemes for introducing the granularity length scale may also affect the propagation of photons by introducing a small dependence of the speed on the photon energy.

These effects on photon propagation are expected to be very small, since their magnitude is set by the ratio of the photon energy over the Planck energy scale ($\sim 10^{28}eV$), but, as I stress in my contribution [14], through the analysis of observations of gamma-ray bursts one has a chance to discover (or rule out) these Planck-scale effects. The properties of gamma-ray bursts that are used in this type of analysis are [15] [16]

- the fact that gamma-ray bursters are often at cosmological distances,
- the fact that a typical gamma-ray-burst spectrum should extend up to the tens of MeV and higher,
- and the fact that some “microbursts” within a gamma-ray burst can have very short duration, as short as $10^{-3}s$ (or even $10^{-4}s$).

The key point I want to stress here is that this use of gamma-ray burst for quantum-spacetime studies is largely insensitive on the nature of the emission mechanism. The properties of gamma-ray bursts which are used are well established, and the analysis is largely independent of the modelling of the emission mechanism. So the convergence of interest on gamma-ray bursts form the exotic-acceleration-mechanisms community and the quantum-spacetime community is accidental.

IV. ON THE MOST ENERGETIC COSMIC RAYS

Several mysteries surround the observation of cosmic rays. This is particularly true for the “ultra-high-energy (UHE) cosmic rays”, with energies higher than $10^{19}eV$. The identification of the particles is problematic, since we reveal them indirectly through their interactions in the atmosphere. It appears however that most UHE cosmic rays are protons.

Most UHE cosmic rays are believed to be of cosmological origin, but this then should imply that the so-called “GZK cutoff” [17] should be observed: the spectrum of observed cosmic rays should basically stop around $E_{gzk} \simeq 5 \cdot 10^{19}eV$, where photons in the Cosmic Microwave Background (CMB) become viable targets for photopion production. A cosmic ray that starts its journey with energy higher than E_{gzk} should lose rather rapidly the energy in excess of E_{gzk} in the form of pions. There is great interest in recent observations of cosmic rays with energies beyond the

¹Some authors have also argued (see, *e.g.*, Ref. [12]) that the quantum-spacetime environment might act in a way that to some extent resembles the one of a thermal environment. It is well established (see, *e.g.*, Ref. [13]) that in a thermal environment the energy-momentum dispersion relations are naturally modified.

GZK cutoff [2] [3].² It has been suggested [4] that perhaps some of the UHE cosmic rays originate from within our galaxy. This would allow them to evade the GZK cutoff, since over “short” (galactic) distances the expected energy loss through photopion production is negligible. But then we should identify within our galaxy some sources that could accelerate protons to such high energies.

So there are issues of interest for the analysis of acceleration mechanisms also in the context of cosmic-ray studies, although of rather different nature with respect to the case of gamma-ray bursts.

V. COSMIC-RAYS AS A QUANTUM-SPACETIME LABORATORY

As I stress in my contribution [14], the mentioned fact that some cosmic-ray observatories have reported above-GZK events has also generated strong interest [19] [20] [21] from the quantum-spacetime research community. This interest originates from the observation that spacetime granularity, besides affecting the laws of particle propagation, can also affect the energetic balance of particle-physics processes. The conventional estimate of the GZK cutoff implicitly assumes that the photopion-production process would occur in an exactly smooth classical spacetime. The GZK scale is set by the minimum energy that, in classical spacetime, is required of a proton to produce a pion in a collision with a photon of CMB energy. In some quantum spacetimes this estimate of the minimum energy is shifted upward by a Planck-scale effect. Of course if the “quantum-spacetime GZK scale” is higher than estimated classically it would be natural to expect some cosmic-ray observations that are above the classical GZK scale.

Essentially these quantum-spacetime-inspired studies are using the cosmic-ray context to probe a regime of high boosts which is not accessible in laboratory experiments. The photopion-production process, $p + \gamma \rightarrow p + \pi$, is well understood and studied in the laboratory at center-of-mass energies that are comparable to the ones available in collisions between a 10^{20} eV proton and a CMB photon, but in our laboratories (when the center-of-mass energies are so high) we are only able to study the process in frames that are not highly boosted with respect to the center-of-mass frame. In the observation of ultra-high-energy cosmic rays we are instead observing (some consequences of) the photopion-production process in a frame which is highly boosted with respect to the center-of-mass frame, involving indeed an extremely hard proton and a very soft photon. The nature of boosts is in one-to-one relation [14] with the short-distance structure of spacetime, and therefore it is not surprising that these studies would be of interest for the quantum-spacetime community.

I here want to stress that once again the convergence of interest on a problem (in this case the cosmic-ray-spectrum problem) by the “acceleration mechanisms community” and the “quantum-spacetime community” is accidental. The new physics associated with spacetime quantization is not being advocated as a way to explain the high energies reached by cosmic rays. Instead the quantum-spacetime community just uses the experimentally-established fact that some cosmic rays have huge energies. From a quantum-spacetime perspective it does not matter how cosmic rays are accelerated to such high energies; it is just a wonderful opportunity that such high-energy particles are available for study.

VI. INTERPLAY BETWEEN THE UNDERSTANDING OF THE EMISSION MECHANISMS AND THE QUANTUM-SPACETIME STUDIES

Up to this point I have stressed that the growing number of instances in which the interests of the “acceleration mechanisms community” and of the “quantum-spacetime community” converge is largely accidental. This needed to be stressed since readers who have not been following closely the development of these fields might quickly assume that the new physics of quantum spacetime is being advocated just as a way to device new acceleration mechanisms, while this is usually not the case. However, I should also stress that there are some issues that require clarification from an acceleration-mechanism perspective and that are quite crucial for the success of the quantum-spacetime studies.

²This AGASA-data-based “GZK puzzle” has been very important in providing motivation for studies of Planck-scale departures from Lorentz symmetry. Even if a future improved understanding of the cosmic-ray spectrum ends up removing the puzzle, the lessons learned for the study of the quantum-gravity problem will still be very valuable. An analogous situation has been rather recently encountered in the particle-physics literature: the discussion of the so-called “centauro events” led to strong theoretical progress in the understanding of the possibility of “misaligned vacua” in QCD (see, *e.g.*, Ref. [18]), and this progress on the theory side remains valuable even though now most authors believe that “centauro events” might have been a mirage

I want to illustrate this point through a specific example that is relevant for the gamma-ray-burst studies here mentioned in Sections 2 and 3. Basically the quantum-spacetime interest in gamma-ray-burst observations originates from the fact that the new Planck-scale laws of particle propagation might attribute different speeds to photons of different energies. The fact that we see some microbursts within a given burst that reach different energy channels of our detectors at the same time, within the accuracy available at our observatories, allows us to set limits on this energy dependence of the speed of photons. The Planck-scale effect could be “discovered” if future more sensitive observatories eventually showed this energy dependence. But of course the analysis would be severely affected if there were poorly understood at-the-source correlations between energy of the photons and time of emission. As observed recently in Ref. [7] it appears that one can infer such an energy/time-of-emission correlation from gamma-ray-burst data. The quantum-spacetime studies will be therefore confronted with a severe challenge of background/noise removal. It will be crucial for the quantum-spacetime analysis to have available a reliable description of the emission mechanism, which could allow to remove the undesired at-the-source effect.

VII. OTHER AREAS OF FUNDAMENTAL PHYSICS

I have so far focused on the fact that some areas of interest from the acceleration-mechanism perspective are also of interest for the investigation of certain quantum-spacetime scenarios. In closing, I want to stress that some of the relevant phenomena are also relevant for other types of fundamental-physics studies. Again, I just illustrate this point through a specific example, which is relevant for the cosmic-ray studies here mentioned in Sections 4 and 5.

As mentioned, the most energetic cosmic rays are most likely protons; however, this does not necessarily imply that they are emitted as protons. We infer that they are protons on the basis of the nature of their interactions in the atmosphere, but it is plausible that the cosmic ray might have started off as some other particle, which then decays into a proton at a relatively small distance from the Earth. This would also be another way to describe the observations of cosmic rays with energies higher than the GZK scale: it could well be that the cosmic ray is originally some exotic particle, which does not lose energy through interactions with CMB photons, and then this particle decays into a proton (plus other particles) only at a relatively small distance from the Earth, when the residual time of travel is not sufficient for substantial energy loss through interactions with CMB photons.

Various new types of particles, that are independently of interest from a particle-physics model-building perspective, have been considered (see, *e.g.*, Refs. [22] [23] [24]) in this cosmic-ray context. Progress in the understanding of the cosmic-ray spectrum could provide insight on these new particle-physics scenarios.

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